# An All Solid State Fault Interrupter Using GTO's

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## ABSTRACT

There exists an acute need for a solid state fault interrupter capable of operating at high voltages and/or high currents, for such applications as command chargers, electromagnetic launchers and other high power conditioning applications. The gate turn-off thyristor (GTO) is suited for this task. This requires series connection of several devices and their support systems (electronic and thermal). Reliable operation depends on devising a control algorithm that will cause the individual GTO's to conduct and recover simultaneously. Computer simulation shows that a window of 100 ns is required, during which time all devices must alter from on to off state, and vice versa, to prevent overvoltages on any device of the chain. A first milestone is the construction and testing of a 5 kV series GTO based switch at modest current densities.

Operation of the 5 kV series stack will be compared to the computer simulation, showing excellent agreement.

This work is supported by the U.S. Army Electronics Technology and Devices Laboratory.

## Introduction

Currently available circuit breaker technology is inadequate with regard to the needs of pulse power. Mechanical circuit breakers are far too slow (on the order of 8 ms) to be effective in the protection of our devices. Moreover, they tend to arc, are massive and bulky and suffer the lack of reliability associated with mechanical systems. The solution to these problems is a solid state circuit breaker and fault interrupter.

Unfortunately, solid state devices have not seen as widespread a utilization as they might have, due to limitations on the voltage capability of single devices.

There are two possible remedies to this situation. The first is to increase the voltage handling capability of the solid state component in question. The second is to arrange several components in series and share the higher voltage levels amongst several devices. The first, though preferable, involves a tremendous commitment of resources and can require long developmental time. The second is the more expeditious and will be the subject of this paper.

## Scope of the Investigation

The object of the investigation is the use of GTO's in series, both experimentally and theoretically. The ultimate goal is to construct a set of two high voltage opening and closing switches. This is being done by modelling the individual devices and devices in series, and verifying the simulation results experimentally. Then a switch will be constructed and tested.

Two switches are proposed. The first, a proof of principle, utilizes 1 kV GTO's to construct a 5 kV switch. The second, more advanced switch, utilizes 4500 V, 2000 A GTO's to produce a 25 kV opening and closing switch. All system components, whenever possible, are to be commercially available components. This places this program in sharp contrast to those that depend on the development of exotic hardware.

## Preliminary Investigation

The devices used in the beginning of the investigation are 1 kV, 160 A GTO's made by International Rectifier. They were tested at voltages up to 800 V in the apparatus whose schematic appears as Figure 1.

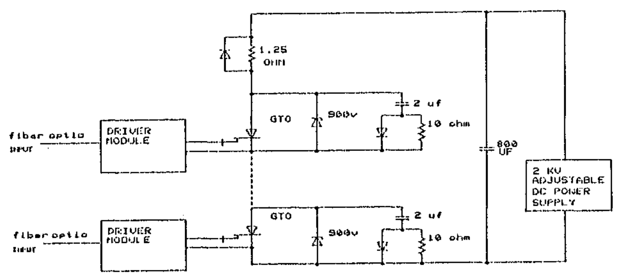


FIGURE 1 Schematic of experimental apparatus, showing identical GTO series stages

The capacitor, resistor and diode network connected across the device under test is referred to as a snubber circuit. Its function is to protect the device under test from voltage and current transients. There are several unique requirements for the snubber components. The diode permits the capacitor to charge quickly and must be of a fast type. The capacitor and resistor must be of low inductance construction, to reduce voltage transients, while absorbing current transients. The manufacturer recommends no more than 30 nH of inductance in the snubber circuit [1].

Previous efforts to series GTO's rate the individual device voltage very conservatively, allowing plenty of margin on the total voltage to account for turn-off spikes [2]. It is the intent of this work to subject the devices to more severe duty by closing these margins.

This is possible by extensive use of computer simulation of the circuit described above. Applicable limits of system inductance were thus determined, for example. The computer modeling was done using commonly available circuit modeling packages, such as MICROCAP and variations of the SPICE family of models. All simulations were run on IBM compatible personal computers.

The device model of the GTO was remarkably simple. Historically, GTO's have been modeled as simple switches [3]. On state and off state resistances are specified by the programmer. Off state values is just a matter of specifying a large (megohms) resistance. The on state is more subtle, requiring the adjustment of the resistance value to accurately reflect the experimental measurement. For this, careful correlation between experimental and calculated values must be done. It was determined that an on state resistance

# Report Documentation Page

*Form Approved*
*OMB No. 0704-0188*



| 1. REPORT DATE | 2. REPORT TYPE | 3. DATES COVERED |
|---|---|---|
| **JUN 1989** | **N/A** | **-** |

4. TITLE AND SUBTITLE
**An All Solid State Fault Interrupter Using GTO's**

5a. CONTRACT NUMBER
5b. GRANT NUMBER
5c. PROGRAM ELEMENT NUMBER

6. AUTHOR(S)

5d. PROJECT NUMBER
5e. TASK NUMBER
5f. WORK UNIT NUMBER

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)
**Department of Electrical Engineering-Electrophysics University of Southern California Los Angeles, California 90089-0484**

8. PERFORMING ORGANIZATION REPORT NUMBER

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)

10. SPONSOR/MONITOR'S ACRONYM(S)

11. SPONSOR/MONITOR'S REPORT NUMBER(S)

12. DISTRIBUTION/AVAILABILITY STATEMENT
**Approved for public release, distribution unlimited**

13. SUPPLEMENTARY NOTES
**See also ADM002371. 2013 IEEE Pulsed Power Conference, Digest of Technical Papers 1976-2013, and Abstracts of the 2013 IEEE International Conference on Plasma Science. Held in San Francisco, CA on 16-21 June 2013. U.S. Government or Federal Purpose Rights License.**

14. ABSTRACT
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15. SUBJECT TERMS

| 16. SECURITY CLASSIFICATION OF: | | | 17. LIMITATION OF ABSTRACT | 18. NUMBER OF PAGES | 19a. NAME OF RESPONSIBLE PERSON |
|---|---|---|---|---|---|
| a. REPORT | b. ABSTRACT | c. THIS PAGE | | | |
| **unclassified** | **unclassified** | **unclassified** | **SAR** | **4** | |

of 1.11 ohms best predicted the behavior of the device, when subjected to experimental measurement.

## Two GTO's in Series Configuration

The simulation model was most useful in predicting the behavior of two GTO's in series. The key parameter was found to be the synchronization of the on and off gating signals to each of the GTO's.

Various versions of the model were run for a variety of time intervals between gating of the two devices. The result of these simulations is shown in Figure 2.

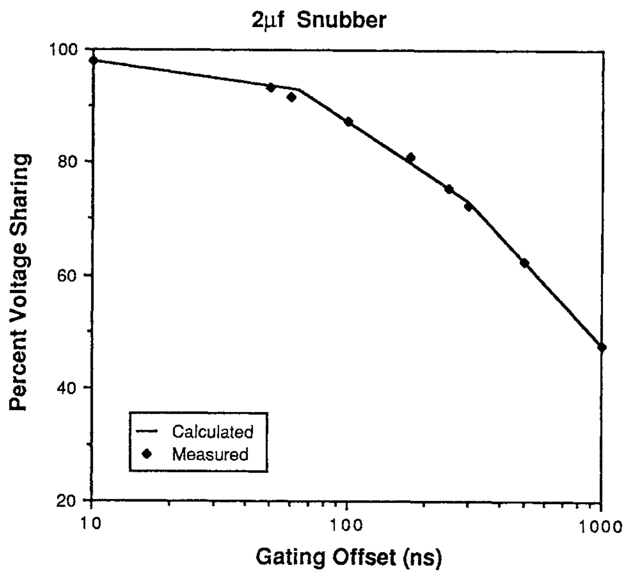


FIGURE 2 Effect of a synchronous gating of two GTO's in series

Nonsynchronous gating of the individual devices produces an unequal sharing of the system voltage across each of the two devices. This is shown on the ordinate of the graph in Figure 2. This is expressed as a quantity known as the percent of sharing, in which one hundred percent denotes an equal sharing of voltage between the two devices; in other words, an even division of system voltages by two, or, each device has half the voltage across it. A sharing factor of eighty percent means one device has only eighty percent of the half voltage across it, while the other one hundred twenty percent of the half voltage across it. In numerical values, if 1 kV were to be placed across the pair of devices, they should ideally carry one half the voltage, or 500 V. If one had a sharing factor of eighty percent, it would be carrying only 400 V while the other would be carrying 600 V, for a sharing factor of one hundred twenty percent. This appears, at first glance, to be a somewhat cumbersome designation, but it is useful as a figure of merit for evaluating the operation of the individual devices in the circuit.

These theoretical results were confirmed experimentally and the results are also displayed in Figure 2. Note the very short interval of asynchronous operation that provides reasonable (eighty percent or better) voltage sharing. We have established a window of triggering of 100 nanoseconds as the maximum allowable asynchronous operation to produce reasonable voltage sharing. We have also established that this margin increases with increasing snubber capacitance for each stage. This finding has less than desirable consequences, in that the snubber capacitors, for more reliable operation, must be physically larger. This did alter our approach to the design of the 5 kV switch, as will be seen later.

These results were not anticipated. It should be mentioned that any unequal voltage sharing, due to asynchronous gating, does not tend to self regulate, making it even more imperative to precisely gate the individual GTO's. This can be explained by an examination of the series of events involved in a commutation. If one device turns off faster than the other, it bears the full voltage less the on state voltage of the other device. The current is also interrupted. When the second device turns off, it acquires a large resistance. This resistance, in the absence of current, subjects the first devices to full voltage on the pair of devices. It becomes, in short, a pull up resistor. It is therefore imperative, when analyzing the circuit, not to consider the GTO's to be perfect switches. The only mitigating factor, which will prevent the GTO's from experiencing full system voltage, of disastrous consequence if the system is to be operated as we intend, is the charging and discharging of the individual snubber capacitors on each GTO stage, which tends to ease the transition of voltage in commutation. Hence, the advantage of using larger values of snubber capacitors.

## The Design of the Five Kilovolt Switch

With this all known, the next step was to design the demonstration 5 kV switch. In keeping with the directive of using only commercially available components, the switch was constructed in a standard printed circuit board card cage, designed for a standard 19 inch rack and to fit behind a 7 inch rack panel, as shown in Figure 3. The only major modification was made at this point, with the installation of the two thick aluminum plates at either end of the card cage. These provide anchorage for the pressure screw and reaction plate, in order to exert the 5.3 KN(1200 Lbf) required to hold to the GTO stack. The stack consists of seven GTO's, each mounted on its own individual circuit board. The board consists of the GTO, snubber circuit, commercial driver module and a small DC power supply. The board is of the perforated, prototyping variety, in order to aid any modifications of design that may prove necessary.

The snubber circuit is of particular note. As previously mentioned, a large value snubber capacitor was found to be beneficial to the operation of the circuit. Conventional capacitors of this capacitance (2 uF) and 1 kV voltage rating were hopelessly large for this application. A new snubber capacitor network design was formulated and the result is shown in Figure 4, along with the capacitors it replaced. The network consists of twenty 100 NF, 1 kV multilayer ceramic capacitors mounted in a radial fashion on a circular printed circuit board, with two concentric traces as terminals for the individual capacitors. The paralleling of many capacitors aids in the reducing of the inductance of the capacitor network. The network sits on top of the GTO, like a hat, and takes up, in addition to very little volume, no board space. Device cooling is accomplished, in this prototype, with small radially fin heat sinks, which were originally designed to cool large IC pin arrays. Although of low power rating, they are more than adequate for our application, in that though our peak power requirement is large, our system is operated in a pulse mode of low duty cycle. For the circuit interrupter application, liquid cooling will be utilized

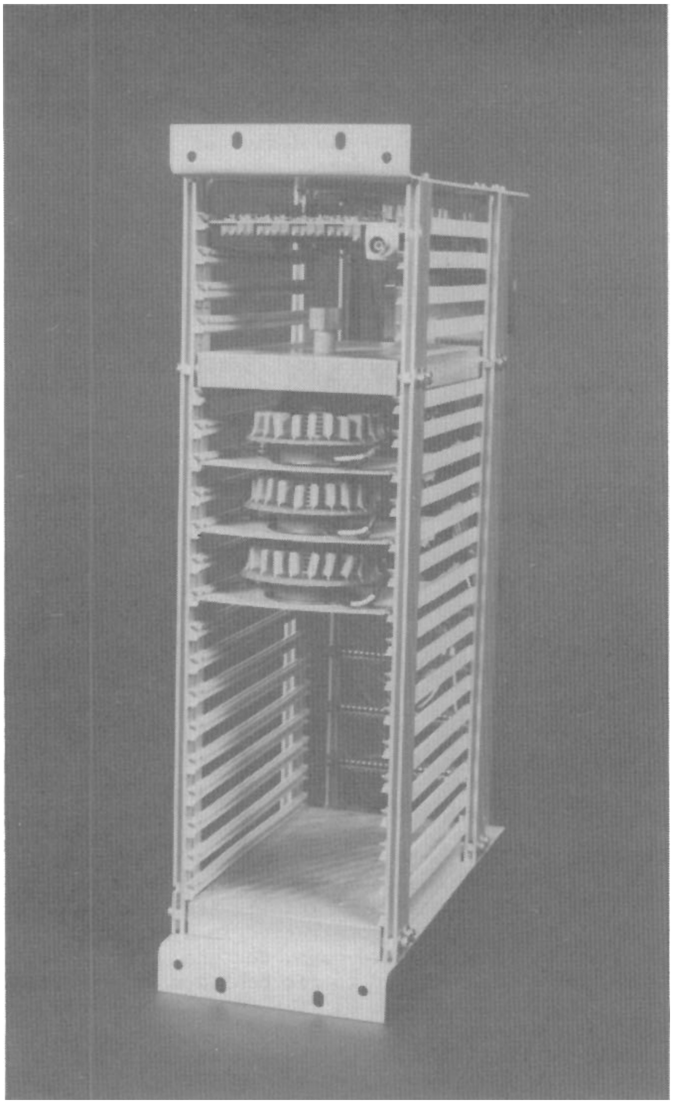

FIGURE 3 5 kV switch rack, with three boards installed

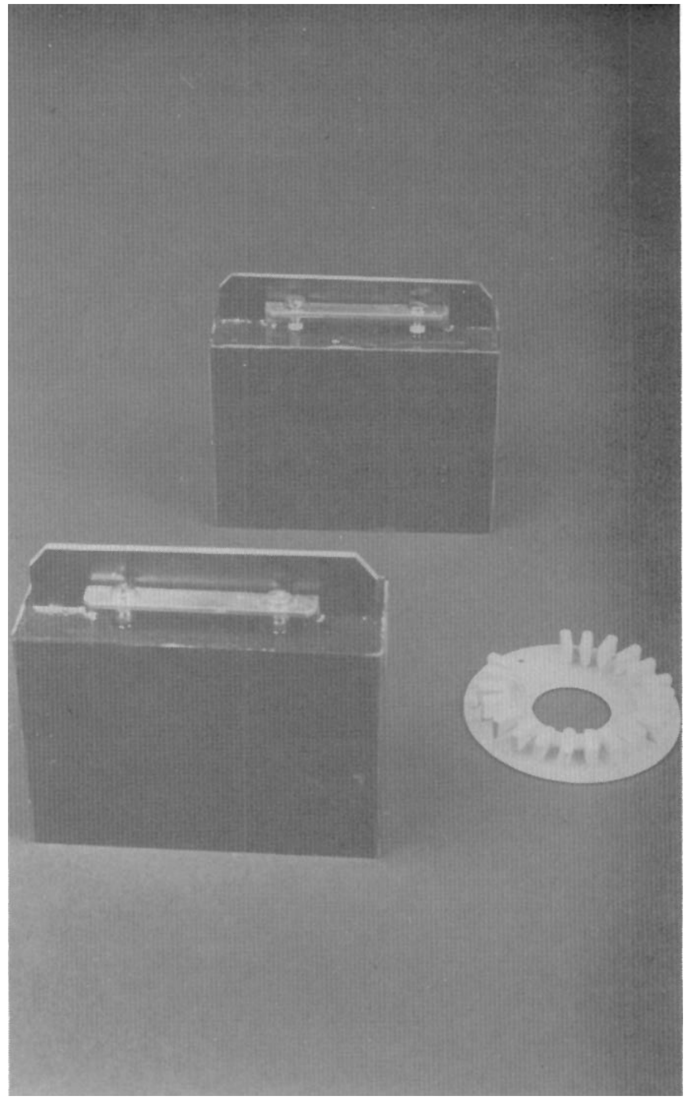

FIGURE 4 Capacitor assembly (right) with the two large capacitors (left) that it replaced

Control and individual triggering of each GTO is done by means of a triggering board, which splits a common control signal into individual control signals, with time variable adjustment on both on and off signals. These signals are carried over to each GTO board via fiber optic, to assure high voltage isolation. The system is first operated at low voltage, the gating signals synchronized and then full voltage applied. Telemetry from each board, via fiber optic, is also possible, although we have had no call for it as of yet. Isolation of the operating power to each board is a major problem. Large isolation transformers are needed to isolate the 110 VAC input power to the power supplies on each board. Upon completion of the present work, that being the demonstration of the 5 kV switch, the task will be to eliminate these large, heavy components. One promising scheme involves recovering, rather than dissipating, the energy in the snubbers and using it to trigger the GTO's on and off. This, however, is a future project.

Current work involves the use of three GTO boards in series. Institutional procurement problems have prevented us from testing the full stack of seven. The situation has recently been rectified and testing of the full scale devices is continuing.

## Conclusions, Applications and Future Work

In closing, we would like to mention some related projects underway at our Laboratory. Our Laboratory has committed to the technology of this paper by embarking on a program to install a solid state, GTO based AC circuit breaker on the main 4160 V power feeds of a 6.6 MW power supply, which is currently installed in our facility. The proposed installation has the following requirements:

Table 1

| | |
|---|---|
| Continuous Current | 600 A |
| Maximum Interrupt Current | 2000 A |
| Surge Current (10 ms Pulse 1 Cycle) | 10000 A |
| Open Time | 300 us |
| Close Time | 50 us |
| Basic Impulse Level | 30 kV |
| Withstand Voltage | 15 kV |
| Steady State Impedance | .05 Ohm |

Although this application is for AC, DC interruption is just as practical.

We have shown the GTO to be capable of the tasks we have set out for it. It does, however, have some drawbacks. The most severe of these is the requirement that it have a large gating current to turn it off. Turn off gain is only about 4 or 5, i.e. to turn off 2000 A, one needs to provide 400 or 500 A turn off current. Hence, the need for large isolation transformers. A new device, the MOS controlled thyristor, or MCT, is currently undergoing testing in our Laboratory. The MCT does everything the GTO does, but, because of the MOS technology, the turn off current is only fractions of amperes. These new devices, which are just now going into commercial production, will have the capability of handling large amounts of power, at high voltages, with very little mass and volume dedicated to their use.

The current technology, and the bright promise for the emerging technology, paints a bright picture for compact, high reliability power handling devices, adaptable to severe constraints and conditions.

## References


[1] International Rectifier GTO manual, 1987

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